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## **Final Report**

**to the Air Force Office of Scientific Research: Physics**

**F49620-96-1-0083**

**Novel Fibers and Photonic Devices**

**January 1, 1996 - December 31, 1999**

**Division of Engineering, Brown University,**

**Providence, RI 02912**

**T.F. Morse, Professor of Engineering**

### **Introduction**

The Laboratory for Lightwave Technology with support from AFOSR, Physics, has continued its efforts to develop new techniques for the processing of photonic materials, in particular optical fibers, and to develop novel sensors for various defense applications. In particular, we have devoted much of the time of this contract toward improvements in optical fiber lasers and toward gathering experience to improve our program in high power, cladding pumped optical fiber lasers. The Laboratory for Lightwave Technology has served as a focus for the fabrication of specialty fibers not only for industry, but for various governmental laboratories such as the Phillips Laboratory, and the Lawrence Livermore Laboratory. In addition, through cooperative research with faculty at other universities, we have been in a position to supply novel rare earth doped fiber lasers. We were able to show that by doping a silica fiber with Nd and Er ions, and by simultaneously pumping with 800 nm radiation (to invert the Nd ions) and with 980 nm radiation (to invert the Er ions) it was possible to obtain lasing at both 1,060 nm and 1537 nm. More recent work has investigated the Tm and Er systems. Since there is a resonance transfer between an upper state of Tm (that can be pumped at 790 nm) and Er, it was possible to pump the Tm at 790 nm and, by lattice energy exchange, to obtain an inversion in the Er that resulted in lasing at 1538 nm. Indeed, by proper adjustment of system parameters, it was indeed possible to pump this system at 790 nm and obtain lasing simultaneously at 1,857 nm and 1,537 nm. We believe that this is the first time that this has been achieved.

### **Temperature Tuning of Fiber Lasers**

We have previously described how an aerosol technique developed in our laboratory has proved to be particularly useful for co-doping optical fiber lasers. The tuning of fiber lasers is important not only for telecommunications, but for spectroscopic and sensing applications, as well as for the creation of efficient optical delay lines for phased array applications. We have reported, under AFOSR support, a new technique by which it is

possible to tune optical fibers over a wide band width. This will be of particular importance for some techniques we have developed for intra-cavity fiber laser spectroscopy.

It is well known that a  $2 \times 2$  fused taper coupler can function as a loop mirror for an optical fiber, either in a ring or a linear configuration. By making a  $2 \times 2$  coupler that is "overcoupled", i.e., many optical cycles during the fabrication process, we obtain what we call a HOCC (Highly Over-Coupled Coupler). If such a coupler is made so that its spectral output has a monotonic decrease over the bandwidth of a fiber laser, and if this device is used as the output coupler, then, as the fiber is strained, or, more easily, temperature tuned, the reflectivity of the loop mirror changes. For a given fiber doping and geometry, if we change the reflectivity of the output coupler, the lasing wavelength will shift. By attaching a loop mirror fabricated from a HOCC to a small Peltier plate, we have been able to temperature tune the wavelength of both linear fiber lasers, and fiber ring lasers. We have continuously tuned an Er laser over the total gain band width from 1,527-1,572 nm with a temperature increase of only 20 degrees centigrade. In addition, as opposed to other techniques for fiber tuning (not using a bulk element such as an intra-cavity grating), the tuning has been continuous. We have also been able to tune the Tm system over 80 nm, and, using different HOCCs as output couplers, over 150 nm total.

This is of importance for some spectroscopic applications, and for possible optical delay lines, if this tuning can be accomplished rapidly enough. Thermal change of the reflectivity of the output coupler, however, can not be rapid enough for an optical delay line, and we have performed the following experiments. If a  $2 \times 2$  Mach Zehnder switch in lithium niobate is used to replace the functionality of the loop mirror, and if the two output arms are connected, we have a similar situation. To overcome losses (approximately 4 dB/pass) in the lithium niobate, the output arms are made of erbium fiber and pumped by 980 nm. We attempted this experiment with lithium niobate devices obtained from Lucent Technologies, and from a 1.3 device fabricated by Uniphase and lent to us by Prof. K. Bergman of Princeton. Unfortunately, the Mach Zehnder configuration was not wavelength dispersive, since this was a balanced Mach Zehnder, designed to give a flat response with respect to wavelength. This is not unexpected, since these devices were for telecommunications applications, and the switching should be relatively wavelength independent. We have, however, located an unbalanced Mach Zehnder lithium niobate device at Tetra-Tech Corporation in California, and they will lend us this. This device does have wavelength dispersive characteristics similar to our loop mirror experiments. We believe that there is a reasonable chance of obtaining tuning over many tens of nm in the erbium system. The switching time of the lithium niobate device will be less than a nanosecond, so the equilibration time will be determined by the time it takes for the laser to "ring down" to the new wavelength. We believe that we can make the total laser length less than a meter, and if 50 round trip times is

the order needed to achieve equilibrium at the new switched wavelength, then we should be able to switch to a new, and significantly different laser wavelength in less than a microsecond.

By putting a changed wavelength into a dispersive, but not necessarily loss, fiber, we have an optical delay line. If this can be switched in a microsecond or less, this has significant implications for phased array radar. We hope to continue these experiments in the near future when we obtain the unbalanced Mach Zehnder device (Uniphase) from Tetrattech.

### **Fiber Laser Intra-Cavity Spectroscopy (FLICS)**

It is well known that when an absorber is placed within a laser cavity it can spoil the gain and give rise to a significant loss of laser power, or an extinguishing of the lasing itself. This concept has been used in the laboratory for the measurement of extremely small amounts of absorber. We have extended this concept to compact fiber lasers. Any absorber can be measured that has an absorption signature under the gain bandwidth of the fiber laser. Of particular interest is the erbium fiber laser, with a tuning range of 1,527 nm to 1,573 nm, and the thulium fiber laser, which exhibits gain between 1,700 and 2,000 nm. Although this is a "narrow band" instrument, there are many important gases to be detected in these wavelength regions. In particular, the sensitivity of the technique is such that overtones may be detected.

We have done initial model experiments with the erbium fiber laser, and we have strain tuned a Bragg grating at 1,533 nm to detect the presence of acetylene, which absorbs in this wavelength region. The line separation of the acetylene is less than 1 nm. If the laser is tuned between these lines, there is no absorption, and if the laser is tuned to an acetylene line, there is a change in intensity of 50 dBm. The problem with such measurements is that there is a relatively large amount of noise in the system. Nevertheless, even this simple detection technique can be used to note the presence of a new class of freon replacements that substitute for Halon flame retardants. These are contemplated for use in the suppression of fires in aircraft. At the present time, the detection of the presence of such gases depends upon diffusion through a membrane, and the response time of such detection is many tens of milliseconds. The use of such a technique would reduce this time to a few microseconds.

One of the techniques that can be used to increase detection sensitivity and reduce noise is that of Balanced Ratiometric Detection. In this concept, the lasing signal is split. One part of the signal passes through the absorber, and one part does not. The two signals are sent into the BRD and their difference is electronically detected. Since the noise in the two signals is identical, the sensitivity of detection is increased significantly. We have used this technique with a Tm fiber laser to detect the third overtone of NO in the 1,800 nm regime. This is a wavelength region in which there are no convenient diode sources available. In addition, the tunability of such diode sources is limited to a few nm.

Since intra cavity spectroscopy holds the promise of great sensitivity, and, in fiber form, in a compact configuration, we have made several attempts to make this process compatible with a two beam system. This would allow BRD techniques to reduce noise. First we placed a beam splitter in front of the absorption cell to direct 1/2 of the cavity light toward another mirror. Thus, we attempted to create a cavity with two independent outputs, but with the same noise. This seemed attractive, but the experiment failed. Although it appeared that there were two cavities, when one cavity was blocked, the other cavity stopped lasing, and vice versa. Thus, the cavities were not independent, and a more complex "Y" shaped cavity was formed. The next modification to this concept was the following. The polarization of the fiber gain medium was controlled by "polarization" paddles, or loops, so that the polarization vector impinged on a polarizing beam splitter at 45 degrees. Thus, "x" polarization went straight through the beam splitter and through the absorption cell, and "y" polarization exited the beam splitter at right angles and impinged upon an broad band output coupler. This resulted in two laser outputs, "x" and "y" polarization; however, the noise in each of the laser signals was identical. If the output of each of the polarizations was sent into a detector, the signal was extremely noisy. When no absorber was placed in the cell, and the BRD was used to subtract the laser output of different polarizations, the response was extremely flat. We have increased the sensitivity of detection over the initial application of FLICS by three orders of magnitude. There are still some problems with phase noise in the system, since the bulk optical components used in our experiments were not properly coated. We have recently received an all-fiber polarization beam splitter from K.O. Hill, of the Defense Research Group in Ottawa, Canada, and further experiments are in progress.

### High Power Cladding Pumped Optical Fiber Lasers

The brightness theorem states that focusing light from one optical medium to another, the product of area and numerical aperture must be constant. For this reason, it is not possible to focus the high output powers available from multiple stripe diodes into the core of a single mode optical fiber. However, by focusing this radiation into a multimode guiding structure in the center of which is a single mode rare earth doped core, the light will, over some distance, interact with the core and be absorbed. Since all of the light focused into the multimode structure will not consist solely of meridional rays, it is necessary to break the symmetry of the structure to prevent helical rays from spiraling around the core. The Polaroid Corporation has patented the concept of a rectangular multimode structure surrounded by a low index plastic, and a single mode core in the center. A recent post-deadline paper at CLEO from SDL (they have purchased the Polaroid fiber facility) has produced 110 W of CW radiation from a single mode Yb core.



In an effort to develop an all-glass cladding pumped fiber later, we have concentrated upon two designs. The first of which results in a numerical aperture approaching 1.0. This is achieved in the following manner. We take a typical rare earth doped optical fiber preform, 14 mm in diameter, and we then wrap this with a 2 mm low index glass rod (obtained from the glass institute in St. Petersburg). The pitch of this helical wrap is also approximately two mm. This "candy cane" is then sleeved with a quartz tube. When this preform is pulled into an optical fiber, there is a great reduction in diameter. The helix, with its original pitch of 2 mm, unwinds, and in the fiber, the pitch of the helix can be as much as 30 cm, depending on the final fiber diameter. Thus, what is achieved is the following. The cross section of the final fiber consists of an outer quartz sleeve, and inside, is the original preform core attached to the outer sleeve by a slender section of low index silica. Thus, except for this low index attachment point at some given axial position, the multimode section of the fiber is surrounded by air, or, by argon. Thus, we have achieved an all glass cladding pumped fiber with an extremely large numerical aperture. The attachment of the low index glass serves also to break the radial symmetry of the distribution of radiation in the fiber, thus preventing the propagation of helical modes that will not interact with the fiber core.

This fiber, at the diameters we have been able to pull this, is relatively fragile as a consequence of the fact that it is not solid glass. We have managed to pull short sections of this fiber manually; however, it is not possible to pull this fiber on our draw tower using a traditional capstan-friction wheel configuration. Efforts are presently being made to obtain a "tractor" puller that is manufactured by Heathway. We hope that Galileo, having recently closed down their operations in Sturbridge, MA, will donate such a piece of equipment to our program.

We are participating in a cooperative program on high energy cladding pumped optical fiber lasers with Dr. Aland Chin, of the Polaroid Corporation. He has agreed to supply us with high energy diode pumps at wavelengths for both our Tm and Er systems, and this work is in progress.

We believe that high power cladding pumped lasers are perhaps the most important development in the past decade in the laser community, and we hope to concentrate more of our efforts in this area.

### **Zeolite and the Elimination of Concentration Quenching**

Work in this area is in a preliminary stage, and we have not yet published. The student working on this area has just completed his Ph.D. preliminary examinations, for which he studied for several months. This successful completion of this key examination will enable him to focus on this important problem in the near future.

Rare earth dopant concentration, particularly the important erbium system, can be increased up to the point at which phase separation occurs in the glass. This would increase the power density in any given fiber laser system; however, long before the glass reaches this unsatisfactory condition, the phenomenon of concentration quenching occurs. Silica forms a tetrahedrally coordinated matrix, with the tetrahedra joined at the apex of the tetrahedra. Trivalent rare earth ions have a different coordination number, and so they do not fit well into the silica host. The addition of aluminum ions tends to "spread" the host somewhat, so that a higher concentration of rare earth ions can be incorporated. As a consequence of this different coordination number, the rare earth ions tend not to be uniformly distributed in the matrix, but to "cluster". This has the following undesirable result. If the rare earth ions are too close together, when one ion is excited, there is a finite possibility that instead of contributing to the power in the radiative field, it will excite a neighboring rare earth ion, and it will de-excite. Thus, this radiative energy can diffuse spatially through the glass, and no lasing photons result.

If it were possible to reduce, or even eliminate this clustering, then higher average concentrations could be achieved. The results would be shorter lasers, more power/unit length, and faster switching. Preliminary experiments inspired by one Japanese paper have indicated one way in this might be accomplished. Zeolite are complex three dimension structures that contain Si, Al, and O ions. There are many types, but these resemble three dimensional "igloos" with many entrances. In each of these entrances, and, indeed, in the main "igloo" itself, it is possible for an ion to be trapped. These ions can be exchanged through the process of diffusion, and it is this characteristic that makes these compounds of importance as ion exchange materials. Typically, Na ions are present in the zeolite traps. In the work referred to above, the authors exchanged the Na with ammonium ions, and then, the ammonium ions were exchanged with neodymium ions. This crystalline material was then processed at a high temperature, and the resulting material was found, under proper processing conditions, to be amorphous. Thus, although the original material was, indeed, a crystalline powder, the final solid material was an amorphous glass. We can imagine a situation in which these crystals bonded to one another, and that the bond lengths became distorted to produce the amorphous solid. This means that there is little to cause scattering in the interaction with light. Lifetimes were measured that were significantly longer than that of the traditional Nd-glass laser system. Measurements indicated that when the Nd ions were removed from the main "igloo" section and allowed only in the "igloo" entrances, that the Nd ions were held at the minimum distance before the onset of concentration quenching.

We have performed two preliminary experiments to determine if the concept just described is compatible with optical fiber processing, since the silica collapse temperature is several hundred degrees larger than either the

decomposition temperature of the zeolite, or the temperatures at which the Nd zeolite system was processed.

By using a modified solution doping technique on the surface of a silica frit inside a preform tube, we have been able to obtain an amorphous zeolite core, in which the index raising component is merely the aluminum. Since the system is not a silica system in which Al is added in an interstitial manner, but a truly amorphous Si-Al-O system that is formed from a distortion of the zeolite crystal structure, we have shown that it is possible to incorporate a larger percent of aluminum than that obtained previously.

Having established the fact that it is possible to fabricate a silica fiber with an amorphous zeolite core, our next efforts will be to fabricate an optical fiber with an erbium doped zeolite core to investigate the reduction of concentration quenching.

### Future Efforts

Below we have listed publications associated with AFOSR support. We believe that our focus will continue to be on high power optical fiber cladding pumped lasers, and we believe that cooperative research programs with Spectra Physics Lasers as well as with the Polaroid Corporation will be established. The use of fiber lasers in spectroscopic applications will continue in cooperation with PSI, Inc., of Andover, MA. NASA has expressed interest in our participating in developing high power cladding pumped Q switched fiber lasers at 944 nm. We believe that recent experiments using a loop mirror and its interaction with a sound wave will lead to a new technique for Q switching, and we hope to demonstrate this in the coming months.

The most important occurrence in our laboratory over the past year has been the decision, after 36 years at Brown, to move to Boston University. I will become a professor of Electrical and Computer Engineering and the Director of the Laboratory for Lightwave Technology at the new Boston University Photonics Center. This laboratory will contain three optical laboratories, several offices, three deposition laboratories, and an optical fiber draw tower. The facility is due to be ready sometime over the summer, and it will consist of 4,000 square feet of state-of-the-art laboratories and offices. In addition to the five laboratories that I will bring from Brown University, a DURIP grant from AFOSR and generous matching funds from the Nextrom (Nokia) Corporation will permit the establishment of a Boston University-Nextrom cooperative project on fiber manufacturing. We are also participating in discussions with Lucent Technologies on the donation of a new, but unused Nextrom draw facility, and that decision should occur within the next few weeks.

The personnel that are going to Boston University place us in a unique position for significant progress in the areas of fiber lasers and fiber sensors, and it is perhaps pertinent to describe the capabilities of these individuals.



Dr. George Wylangowski, Research Associate Professor, has a Ph.D. in chemistry and was Principal Experimental Officer at Southampton for 13 years. Not only has he a deep and profound understanding of fiber processing with regard to technology as well as chemistry, he has such familiarity with the equipment that anything can be repaired.

Dr. Valerii Kozlov, Research Assistant Professor, has a Ph.D. from Moscow State University in Physics, and his expertise in fiber lasers and high power diodes will be invaluable to our program in cladding pumped fiber lasers.

Dr. Fei Luo, Visiting Research Associate Professor from Nanjing University, has expertise in optical fiber sensors. He is the key member of our group in this area.

Dr. Juan Hernandez-Cordero has just finished his Ph.D. in spectroscopic applications of optical fiber lasers, and he will be coming to the group at Boston University as a Post Doctoral Research Associated.

SR Han has a M.Sc. in fiber processing from KIST, and he will specialize in preform fabrication.

#### **Selected Recent Publications: AFOSR support**

1. Kyunghwan Oh, T.F. Morse, L.Reinhart, "Generation of continuous wave oscillation in multiple wavelength from a Tm+3 doped Ta<sub>2</sub>O<sub>5</sub>-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> glass fiber", SPIE Vol. 2778, Optics for Science and New Technology, 718 (1996)
2. Kyunghwan Oh, T.F. Morse, L. Reinhart, "Observation of upconversion fluorescence from Ho+3 ions assisted by energy transfer and excited state absorption in a Tm+3-Ho+3 codoped silica fiber" SPIE Vol. 2778, Optics for Science and New Technology, 803 (1996)
3. Kyunghwan Oh, T.F. Morse, L. Reinhart, "Observation of refractive index change in Sm+2/Sm+3 doped aluminosilicate fiber by irradiation of Ar ion laser", The first Optoelectronics Conference (OECC96) sponsored by The institute of Electronics, Information and Communication Engineers, Technical Digest, 17C2-2, (1996) Makuhari Messe, Japan.
4. Kyunghwan Oh, Un-Chul Paek, T. F. Morse, "Photosensitivity in Multi-Valent Rare Earth Ion doped Aluminosilicate Glass Optical Fiber" Bragg Gratings, Photosensitivity, and Poling in Glass Fibers and Waveguides: Applications and Fundamentals, sponsored by OSA and American Ceramic Society, Technical Digest, JSuE-018 (1997) Williamsburg, USA,
5. Kyunghwan Oh, Un-Chul Paek, T.F. Morse, "Infrared absorption spectroscopic gas sensor using an amplified spontaneous emission light source from a Tm+3/Ho+3 co-doped silica fiber" 12'th International Conference on Optical Fiber Sensors sponsored by OSA, Technical Digest, OThC7 (1997) Williamsburg.
6. Kyunghwan Oh, Un-Chul Paek, T.F. Morse, L. Reinhart, Arnd Kilian, "Photoinduced refractive induced change in Sm+2/Sm+3 codoped

aluminosilicate fiber by irradiation of an Ar ion laser", *Optics Letters*, Vol. 22, No. 15, 1192 (1997).

7. V.A. Kozlov, R.L. Shubochkin, A. Kotze, H. Kung, D.A. Brown, E. Wetjen, A.L.G. Carter and T.F. Morse Temperature tunable Er- and Tm-doped fiber lasers Advanced Solid-State Lasers Topical Meeting, paper AMB3, Coeur d'Alene, Idaho, February 2-4, 1998.

8. V.A. Kozlov, R.L. Shubochkin, A. Kotze, E. Wetjen, A.L.G. Carter, H. Kung, D.A. Brown and T.F. Morse, "A New Technique for Continuously Tuning of Optical Fiber Lasers", *Applied Optics*, 1998, 37, No. 21, pp. 4897-4901.

9. R.L. Shubochkin, V.A. Kozlov, A.L.G. Carter and T.F. Morse, "Tunable thulium-doped all-fiber laser", *IEEE Photonics Technology Letters*, 1998, 10, No. 7, p. 944-945.

10. J. Hernandez-Cordero, V.A. Kozlov and T.F. Morse, "Fiber laser polarization tuning using a Hi-Bi fiber Bragg grating", *IEEE Photonics Technology Letters*, 1998, 10, No. 7, pp. 941-943,

11. Kyunghwan Oh, T. F. Morse, "Analysis of spectroscopic characteristics of Er doped Ta<sub>2</sub>O<sub>5</sub>-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> optical fiber", The 3rd International Meeting of Pacific Rim Ceramic Society, Symposium for advances in photonic glasses, paper 16-O-2, Kyungju, Korea, September 20-23, 1998.( to be published in *Journal of Non-crystalline Solids*)

12. Kyunghwan Oh, T. F. Morse, "Thermal effects on the excited state absorption and upconversion process of erbium ions in germanosilicate optical fiber", The 3rd International Meeting of Pacific Rim Ceramic Society, Symposium for advances in photonic glasses, paper 16-P-12, Kyungju, Korea, September 20-23, 1998. ( to be published in *Journal of Non-crystalline Solids*)

13. Kyunghwan Oh, A. Kilian, and T. F. Morse, "A new gas detection technique utilizing amplified spontaneous emission light source from a Tm<sup>3+</sup>/Ho<sup>3+</sup> co-doped silica fiber in the 2.0  $\mu$ m region," *Measurement Science and Technology*, Volume 9, Issue 9, pp. 1409-1412, September 1998